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Numerical Investigation of Plasma Detachment in Magnetic Nozzle Experiments

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At present there exists no generally accepted theoretical model that provides a consistent physical explanation of plasma detachment from an externally-imposed magnetic nozzle. To make progress towards that end, simulation of plasma flow in the magnetic nozzle of an arcjet experiment is performed using a multidimensional numerical simulation tool that includes theoretical models of the various dispersive and dissipative processes present in the plasma. This is an extension of the simulation tool employed in previous work by Sankaran *et al.*[1–4] The aim is to compare the computational results with various proposed magnetic nozzle detachment theories to develop an understanding of the physical mechanisms that cause detachment. An applied magnetic field topology is obtained using a magnetostatic field solver (see Fig. 1), and this field is superimposed on the time-dependent magnetic field induced in the plasma to provide a self-consistent field description. The applied magnetic field and model geometry match those found in experiments by Kuriki and Okada.[5] This geometry is modeled because there is a substantial amount of experimental data that can be compared to the computational results, allowing for validation of the model. In addition, comparison of the simulation results with the experimentally obtained plasma parameters will provide insight into the mechanisms that lead to plasma detachment, revealing how they scale with different input parameters. Further studies will focus on modeling literature experiments both for the purpose of additional code validation and to extract physical insight regarding the mechanisms driving detachment.

I. Introduction

MAGNETIC nozzles are used in many experiments to control – confine, cool, accelerate, and direct – plasma flows using magnetic fields in lieu of material boundaries. Studies of plasma detachment have been motivated by its role in many astrophysical phenomena and by the various terrestrial applications that use magnetic nozzles to exhaust power and particles. These applications include plasma flows in fusion systems where understanding detachment is important to controlling the thermal loads on components, rapid plasma cooling for laser emission where understanding recombination during the expansion is crucial to the generation of a population inversion, and directional control of a plasma jet in etching processes. We focus on the role an applied magnetic field and magnetic nozzle can play in facilitating the transfer of random thermal energy into directed kinetic energy in a plasma thruster.

Since magnetic fields are solenoidal, the design of a magnetic nozzle for a plasma thruster involves conflicting goals of confinement (leading to energy conversion and plasma acceleration along the magnetic field) and detachment (allowing for plasma motion transverse to the magnetic field leading to momentum transfer and thrust production). For a thruster it is important to understand the process of plasma detachment from an applied magnetic field both in terms of developing a capability to accurately model the process and for the development of a basic physical understanding of the process, with the end goal being a better understanding of thrusters that employ magnetic nozzles.

While there have been many experimental and analytical efforts to investigate detachment mechanisms, multidimensional numerical investigations have been sparse. Plasma properties in real devices can vary significantly in space and time. Such variations, as well as the complicated magnetic field topologies found in many nozzles, make analytical treatments of detachment difficult if not wholly intractable. In addition many atomic and plasma kinetic phenomena, such as the values of various transport coefficients or the non-ideal relationship between the pressure, density, and temperature as well as their relationship with the ratio of specific heats in the plasma, cannot be easily measured with common experimental diagnostics but can greatly affect the detachment process. Consequently, numerical simulations

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that incorporate realistic models of the various plasma processes can play a unique role in developing an understanding of the mechanisms that cause detachment and learning how these processes scale with various plasma and applied field properties.

In this paper, we discuss the recent development of multidimensional numerical tools that can be used to investigate plasma detachment mechanisms. The numerical code is based on a conservation formulation of the magnetohydrodynamic (MHD) equations, and contains models for various classical and anomalous transport phenomena and a real (non-ideal) equation of state. The code was introduced in Ref. [6] and has been previously used to simulate self-field magnetoplasmadynamic thrusters (MPDT)[1,2] and a lithium Lorentz force accelerator.[3] The capabilities of the code are significantly enhanced over those previous studies, resulting in the capability to model plasma flows in magnetic nozzles. In addition, the code could also be used to simulate applied-field MPDTs, which incorporate the processes found in an MPDT with the magnetic nozzle field topology. The results from previous validation efforts[4] suggest that certain difficulties encountered when applying other MHD simulation codes to the magnetic nozzle problem may not arise in our numerical studies. In the present work we model the experimental work performed in Ref. [5] and compare our computational results with available literature data to explain various experimental observations and gain insight into the physical processes associated with plasma flow and detachment in a magnetic nozzle.

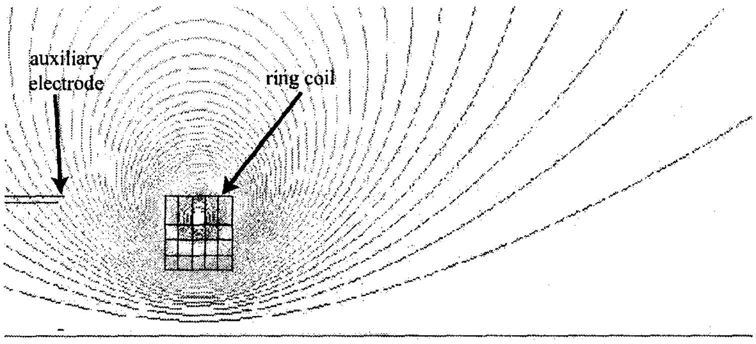

Figure 1. Magnetostatic simulation of flux lines in the $r-z$ plane of the nozzle in Ref. [5].

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